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Transient Absorption Features in GRBs and Their Implications for GRB Progenitors

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ABSTRACT

The recent detection of a transient absorption feature in the prompt emission of GRB 990705 has sparked multiple attempts to fit this feature in terms of photoelectric absorption or resonance scattering out of the line of sight to the observer. However, the physical conditions required to reproduce the observed absorption feature turn out to be rather extreme compared to the predictions of current GRB progenitor models. In particular, strong clumping of ejecta from the GRB progenitor seems to be required. Using detailed 3D hydrodynamic simulations of supernova explosions as a guideline, we have investigated the dynamics and structure of pre-GRB ejecta predicted in various GRB progenitor models. Based on our results, combined with population synthesis studies relevant to the He-merger model, we estimate the probability of observing X-ray absorption features as seen in GRB 990705 to $\ll 1$ %. Alternatively, if the supranova model is capable of producing highly collimated long-duration GRBs, it may be a more promising candidate to produce observable, transient X-ray absorption features.

Subject headings: galaxies: active — gamma-rays: theory

1. Introduction

Recently, Amati et al. (2000) have reported the detection of a transient absorption feature, consistent with a redshifted Fe K edge at the redshift of the burst, $z = 0.86$ (see Lazzati et al. (2001)), in the prompt X-ray emission from GRB 990705. This is the second time (after GRB 980329; Frontera et al. (2000)) that X-ray spectroscopy during the prompt phase of a GRB revealed evidence for excess soft X-ray absorption above the Galactic hydrogen column, and the first time that evidence for a time dependence of such absorption has been found. (Here, we do not consider the possible absorption features detected by Ginga in a few cases [see, e.g., Yoshida et al. (1992)] at higher energies which were inconsistent with being due to photoelectric absorption or other atomic processes.) The transient nature of the absorption feature was rather significant: The absorption edge was detected at the $\sim 12\sigma$ level in observing interval B (with its depth being consistent with the less significant detection in interval A), while there was $< 2\sigma$ evidence for such an absorption edge in observing interval D (and all following intervals), when the upper limit on its depth was inconsistent with the value measured during interval B at the $\geq 5\sigma$ level. This has been interpreted as evidence for photoionization of the absorber by the prompt burst emission (Amati et al. 2000; Böttcher et al. 2001a,b). In contrast to the non-transient excess absorption in GRB 980329 (Frontera et al. 2000), which does not yield very specific information about the location of the absorbing material, the transient nature of an X-ray absorption feature allows rather detailed diagnostics of the relevant physical time scales and the geometry of the GRB environment.

If the observed absorption feature is due to photoelectric absorption at the Fe K edge, then it is natural to try to interpret the duration of the occurrence of this feature as the photoionization time scale, assuming that the absorbing material is not dense enough for recombination to be efficient. The expected X-ray absorption signatures of such a scenario had been investigated previously by Böttcher et al. (1999) who had concluded that such features are either transient on the prompt GRB time scale, or remain virtually unchanged throughout the prompt and afterglow phase. However, the application of this idea to the specific case of GRB 990705 by Böttcher et al. (2001a) revealed that either an implausibly large amount of iron, concentrated very close to the GRB, would be required, or the iron would have to be distributed very anisotropically around the burst source.

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As an alternative, Böttcher et al. (2001a,b) have investigated an environment containing small, dense clumps of iron-enriched material. In such an environment, photoionization can be balanced by rapid recombination, and the duration of the absorption feature can be identified with the Compton heating time scale of the absorber by the prompt GRB emission, or with the sweep-up time scale of the absorbing material by the relativistic blastwave responsible for the GRB and afterglow emission. This scenario can produce the observed absorption feature in GRB 990705 with a reasonable amount of iron, quasi-isotropically distributed around the GRB source, but required that the clumps containing this material be very dense and exhibit a rather extreme degree of clumping.

Finally, Lazzati et al. (2001) have suggested that the absorption feature could be a blue-shifted resonance scattering feature in an inhomogeneous high-velocity outflow. This requires that the absorbing material has a systematic average outflow velocity of $v_0 \sim 0.13$ c and a velocity dispersion $\Delta v \sim v_0$. While this scenario can slightly reduce the required amount of iron and degree of clumping, it requires a kinetic energy of $\sim 10^{53}\,(\Omega/4\pi)$ ergs in the directed outflow, which has to be ejected several months prior to the GRB.

The parameter estimates resulting from all three of these basic scenarios are summarized in Table 1. Those estimates are rather generic and independent of specific progenitor scenarios. In this paper, we are tying parameter estimates pertaining to the transient absorption feature in GRB 990705 to specific GRB progenitor models. This is done by deducing constraints on the supernova explosion which is likely to have happened prior to the GRB, ejecting the material responsible for the transient absorption feature. In §2 we briefly review the viable GRB progenitor models which are generally capable of producing a significant concentration of high-Z material close to the GRB prior to the actual GRB event. The degree of clumping of matter ejected in supernova explosions will be discussed in §3. Model-specific estimates of the parameters pertaining to the pre-ejected material will be calculated in §4. We will discuss the implications of our results in §5.

2. GRB models with pre-GRB supernovae

With most long-duration GRB progenitors it is hard to produce a sizable amount of iron within 1 pc of the GRB engine. For most collapsar progenitors the only source of iron prior to collapse would be in the massive star's wind. Unless these stars are extremely metal rich, the total mass in iron in these winds will be much less than 0.1 $M_{\odot}$. Unfortunately, metal rich massive stars lose too much mass to winds and will probably not form collapsars (Fryer 2001).

The evolutionary scenario of He-merger GRBs provides a more likely, although still rare, source of iron within ~ 1 pc of the GRB engine. Recall that the formation process of a He-merger GRB requires a binary system whose primary evolves to collapse and produces a compact remnant. Normal supernova explosions eject from 0.002-0.3 $M_\odot$ of ^{56}Ni (Turatto et al. 1998; Schmidt et al. 1994) into the region surrounding the binary system and this ^{56}Ni ultimately decays into iron. It is possible that the primary produces an abnormal supernova like supernova 1998bw which then may eject as much as a solar mass of ^{56}Ni or more (Sollerman et al. 2000; Germany et al. 2000). When the primary remnant eventually merges with its companion, a GRB is formed, exploding into this iron rich region.

The difficulty lies in limiting the iron to a region within ~ 1 pc of the binary system until the merger occurs and a GRB is produced (see the values of x in Tab. 1). Because the ^{56}Ni is produced in the inner layers of an exploding supernova and a large fraction of ^{56}Ni is ejected at low velocities (~ 1000 km s^{-1}). Although these velocities are relatively low, it takes only 1000 yr for this ejecta to travel 1 pc. Even if a sizable amount of ^{56}Ni is ejected with lower velocities, winds from the companion star (which tend to be massive for most He-merger GRBs) will blow the ^{56}Ni away from the binary at roughly 1000 km s^{-1} and it is difficult to increase the maximum allowed time delay between primary supernova and GRB outburst (to be consistent with the previous parameter estimates for the absorber in GRB 990705) by less than 1000 yr.

With the standard formation scenario of He-merger GRBs, such small delays between supernova explosion and GRB outburst require that the secondary star evolve off the main sequence a scant 1000 yr after the primary supernova explosion. This would require extreme fine tuning of the masses of the two stars and the likelihood of such an occurrence would be less than 0.01 %.

However, an alternate formation scenario may be more plausible. If the secondary evolves off the main sequence before the primary explosion, a common envelope phase will occur where two helium cores tighten their orbits as they inspiral within a hydrogen common envelope. Typically, after the hydrogen envelope is ejected, it leaves behind two tightly orbiting helium cores. When the primary's helium core collapses, the system may be disrupted by neutron star kicks, it may remain bound, or the neutron star may be placed in such a close orbit that it quickly merges (within 1000 yr) with its helium star companion. The latter case, where the neutron star merges with its helium companion, produces a He-merger GRB surrounded by the iron ejecta of the primary's supernova. Using the binary population synthesis code developed in Fryer, Burrows, & Benz (1998), we have calculated the rate of these quick He-merger GRBs for a range of population synthesis parameters. The fraction of quick mergers lies somewhere between 0.5-2.5 %. For most of the double helium cores which actually form He-merger GRBs, there is typically a delay of 10-100 years from the supernova explosion to the GRB outburst.

SN - GRB delays significantly below $\sim$ 10 yrs could occur in the supranova model of Vietri & Stella (1998), where the supernova explosion of a fast rotating, massive star leaves behind a rapidly spinning, supra-massive neutron star which implodes several months to several years later to form a GRB. The time delay between the SN and the GRB will then be determined by the spin-down time, which can be estimated as $t_{sd} \sim 10\,(j/0.6)\,\omega_4^{-4}\,B_{12}^2$ yr, where j is the dimensionless angular momentum of the neutron star, ω_4 is its angular velocity in units of 10^4 s^{-1}, and its surface magnetic field is $B = 10^{12}\,B_{12}$ G. Detailed simulations of collapsing neutron stars (Ruffert, Janka, & Schaefer 1996; Fryer & Woosley 1998) seem to indicate that, in contrast to Vietri & Stella's original suggestion, this process ejects a rather large amount of baryonic material and has too little energy to produce a GRB. However, strong beaming of a relativistic outflow along the rotational axis may overcome the latter problem so that we will consider the supranova model as a conceivable alternative in this paper, although more detailed simulations are needed in order to address the concerns mentioned above.

3. Clumping of ejecta

Supernova 1987A surprised astronomers by giving strong evidence that the ^{56}Ni ejected in the explosion was mixed into the outer layers of the star (Dotani et al. 1987; Itoh et al. 1987; Sunyaev et al. 1987; Matz et al. 1988). This ^{56}Ni fragmented into high velocity "bullets" (Spyromilio et al. 1988) which could potentially be the clumps necessary to explain the absorption feature in GRB 990705. It is believed that Rayleigh-Taylor instabilities which arise when the shock moves through the composition layers of the star produce this mixing and lead to clumps of ^{56}Ni on size scales from 1 to 5 degrees (see Herant & Woosley (1994), Kifonidis et al. (2000) and references therein). Spatially resolved spectroscopy of Galactic SNRs by the *Chandra* X-ray Observatory (e.g., Hughes et al. (2000); Hwang, Holt, & Petre (2000)) confirmed the tendency of element mixing and clumping of the high-z material into dense blobs in SNRs.

This is in agreement with detailed 3D hydrodynamic simulations of SN explosions as described in detail in Fryer, Hungerford, & Warren (2001). Fig. 1 illustrates an example of the slightly asymmetric supernova explosion of a $15\,M_\odot$ star. The figure shows the distribution of the ejecta, color-coded by the average atomic weight, 1 yr after the SN explosion. It shows that most of the heavy elements are concentrated in dense clumps of angular size scale ~ 1 – a few degrees, and are concentrated around $\overline{x} \sim 5 \times 10^{15}$ cm at that time.

In the following, we will use the results the parameters of the supernova ejecta derived from this example to estimate the expected spatial distribution and, consequently, the expected time-dependent absorption features produced in pre-GRB supernova ejecta in the He-merger and the supranova scenarios. For this purpose, we assume that the metal-rich, dense clumps are not decelerating significantly, so that their distance from the center of the explosion scales linearly with the SN-GRB time delay Δt. Different GRB progenitor models will then differ primarily by Δt and by the amount of mass in the clumpy ejecta, $M_{\rm cl}$, which might be correlated with the mass of the progenitor. We are thus interested in the location of model systems in the $M_{\rm cl}$-Δt plane which are capable of reproducing the absorption feature seen in GRB 990705.

As mentioned above, the directed velocity of clumps containing an overabundance of heavy elements, might be $v_0 \lesssim 10^9$ cm s^{-1}. According to the analysis of Lazzati et al. (2001), this would produce too narrow an absorption feature at a too low centroid energy, if the dominant absorption mechanism were resonance scattering out of the line of sight by hydrogen-like iron. For this reason, we will concentrate in the following on photoelectric absorption as the dominant absorption mechanism.

4. Absorption features from pre-GRB supernova ejecta

As motivated above, we assume that most of the iron is concentrated in metal-rich clumps on angular scales of $\theta_{\rm cl} \sim \theta_{\rm cl,0}$ degrees, with $\theta_{\rm cl,0} \sim 1 - 5$, within which the average atomic weight $\overline{A} \sim 40\,\overline{A}_{40}$ may exceed $\overline{A}_{40} \sim 1$. Those clumps are filling a fraction $f = 1\,f_{-2}$ % of the volume within a typical size scale of $x_{\rm max} = 10^{16}$ cm 1 yr after the supernova explosion. As a function of the time delay $\Delta t = 1\,t_y$ yr, between the SN explosion and the GRB, the spatial distribution of clumps will extend out to $x_{\rm max} \sim 10^{16}\,t_y$ cm. Assuming that most of the clumps will be concentrated around $\overline{x} \sim x_{\rm max}/2$, this yields a typical size scale of such clumps as $r_{\rm cl} \sim 9 \times 10^{13}\,t_y\,\theta_{\rm cl,0}$ cm. For a total supernova ejecta mass concentrated in clumps, $M_{\rm cl} = m_{\rm cl}\,M_\odot$, we then find the average density of nuclei in the clumped ejecta to be

$$n_{\rm cl} \sim 2.9 \times 10^{10}\,\frac{m_{\rm cl}}{\overline{A}_{40}\,f_{-2}\,t_y^3}\ {\rm cm}^{-3}. \tag{1}$$

We would then expect to have $N_{\rm cl}^{\rm l.o.s.} \sim 0.6\,f_{-2}/\theta_{\rm cl,0}$ clouds located by chance along the line of sight towards the observer. If $N_{\rm cl}^{\rm l.o.s.} > 1$, we would thus expect to have several clouds overlapping along the line of sight, while for $N_{\rm cl}^{\rm l.o.s.} < 1$, this number would correspond to the probability $P_{\rm cl}^{\rm l.o.s.}$ of one cloud being located along the line of sight. The initial depth of the iron K absorption edge of clouds along the line of sight (assuming that we have at least

1 cloud located within the line of sight) will add up to

$$\tau_{\rm Fe,cl} \sim \begin{cases} 6.5 \, \frac{m_{\rm cl} \, X_1^{\rm Fe}}{\overline{A}_{40} \, t_y^2} & \text{if } N_{\rm cl}^{\rm l.o.s.} \geq 1, \\ \\ 11 \, \frac{m_{\rm cl} \, X_1^{\rm Fe} \, \theta_{\rm cl,0}}{\overline{A}_{40} \, f_{-2} \, t_y^2} & \text{else} \end{cases} \tag{2}$$

The observation of $\tau_{\rm Fe,cl} \sim 1.6$ during the first ~ 13 s of GRB 990705 can be used to put parameter constraints on the progenitor of this GRB. Assuming that $P_{\rm cl}^{\rm l.o.s.} \leq 1$, this yields

$$m_{\rm cl} = 16 \, t_y^2 \, \frac{P_{\rm cl}^{\rm l.o.s.} \, \overline{A}_{40}}{X_{\rm Fe}}. \tag{3}$$

This relation is plotted for various ratios $P_{\rm cl}^{\rm l.o.s.} / X_{\rm Fe}$ and $\overline{A}_{40} = 1$ by the solid curves in Fig. 2.

Normalizing the spectrum and luminosity of the ionizing radiation to the observed spectrum of GRB 990705 during the first ~ 20 sec, we find a time scale (in the cosmological rest frame of the GRB) for complete ionization of initially neutral iron of $t_{\rm ion}(z) \sim 2.5 \times 10^{-4} \, t_y^2 \, h_{70}^2$ s. For comparison, the recombination time scale can be estimated to $t_{\rm rec}(z) \sim 9.1 \times 10^{-2} \, T_3^{3/4} \, \overline{A}_{40} \, f_{-2} \, t_y^3 / [(Z_{\rm eff}/10)^2 \, m_{\rm cl}]$ s, where T_3 is the average electron temperature in the clumps in units of 10^3 K, and $Z_{\rm eff}$ is the average effective ion charge of iron ions in the clumps.

If recombination is inefficient, then the expression for the ionization time scale allows an estimate of the time delay t_y from $t_{\rm ion}(z) \sim 6$ s. We find

$$t_y = 63 \, h_{70} \left(\frac{t_{\rm ion}[z]}{\rm s} \right)^{1/2}. \tag{4}$$

This relation is shown for $t_{\rm ion} = 6$ s (which might be the appropriate time-scale, in the cosmological rest frame of GRB 990705, of the occurrence of the absorption feature) and $h_{70} = 1$ by the long-dashed vertical line in Fig. 2.

If we require recombination to compete successfully with photoionization, then a comparison of the respective time scales yields

$$m_{\rm cl} \geq 364 \, \frac{T_3^{3/4} \, \overline{A}_{40} \, f_{-2}}{(Z_{\rm eff}/10)^2} \, t_y. \tag{5}$$

The most conservative limit can be found if we consider recombination from fully ionized iron, i.e. $Z_{\rm eff} = 26$, in which case we find $m_{\rm cl} \geq 54 \, f_{-2} \, t_y$ for $\overline{A}_{40} = T_3 = 1$. This relation is indicated by the shaded regions in the upper-left corner of Fig. 2 for $f_{-2} = 1$ and

$f_{-2} = 0.1$, respectively. If recombination is successfully competing with photoionization, then the decline of the Fe K absorption edge in GRB 990705 could be due to Compton heating of the electrons in the clouds. The Compton heating time scale in the clouds can be estimated through $t_h(z) \sim 3.8 \times 10^{-3}\, t_y^2\, h_{70}^2\, T_3^{0.1}$ s, which leads to

$$t_y = 16 \left(\frac{t_h[z]}{\mathrm{s}}\right)^{1/2} h_{70}^{-1}. \tag{6}$$

Using $h_{70} = 1$ and $t_h = 6$ s, this relation is plotted by the dot-dashed vertical line in Fig. 2.

Alternatively, the disappearance of the absorption feature could be due to sweeping-up of the absorber by the relativistic blast wave associated with the GRB. Assuming that during the prompt GRB phase the relativistic blast wave is in the coasting phase, moving at a constant bulk Lorentz factor $\Gamma = 10^3\,\Gamma_3$, we find for the sweep-up time: $t_{sw}(z) \sim x/(2\Gamma^2 c) \sim 8 \times 10^{-2}\, t_y/\Gamma_3^2$ s which, when set equal to the ~ 6 s time scale of the absorption feature, yields

$$t_y \sim 72\,\Gamma_3^2 \tag{7}$$

For $\Gamma = 100$, 300, and 10^3, this is plotted by the dotted vertical lines in Fig. 2.

5. Discussion

The transient absorption feature in GRB 990705 places stringent constraints on the GRB progenitor parameters. In Fig. 2, allowed parameter constellations have to be located in two regions: a) close to the vertical line $t_{\rm ion} = 6$ s, or b) in the shaded region in the upper-left portion of the graph. Case a) corresponds to a pure photoionization scenario, in which recombination in the absorber is inefficient; case b) corresponds to a balance of ionization and recombination. At the same time, ejecta masses significantly exceeding $\sim 10\,M_\odot$ may be ruled out. Also, any solution far left of the vertical line corresponding to $t_{sw}(\Gamma_3 = 0.1) = 6$ s are implausible since this region of parameter space would require $\Gamma_0 \ll 100$, in which case $\gamma\gamma$ opacity effects might become significant. Solutions near the lower right corner of the diagram would require a very strong iron overabundance w.r.t. the standard solar-system value, and a small covering fraction of the absorber, implying a small chance probability of having an absorbing cloud in the line of sight to the observer.

This leaves only a very limited region of parameter space to explain the absorption feature in GRB 990705. The solution at $\Delta t \sim 150$ yr, corresponding to the no-recombination case, is in principle accessible to the quick He-merger scenario, but requires an ejecta mass of $M_{\rm cl} \gtrsim 10\,M_\odot$, a large iron overabundance, and a small covering fraction, $P_{\rm cl}^{\rm l.o.s.}/X_{\rm Fe} \lesssim 10^{-3}$. This small chance probability factors in with the already small probability of $\sim 0.5 - 2.5$ %

of quick He-mergers among the total number of expected He-merger GRBs to yield a total probability of $\ll 1$ % of observing an absorption feature as seen in GRB 990705. Consequently, if similar absorption features will be detected (e.g., by the Swift satellite, currently scheduled for launch in 2003) in other GRBs, this may be a strong indication that at least this type of GRBs might not be related to collapsars or He-mergers.

The second allowed region of parameter space is located at time delays of $\Delta t \sim 1$ yr and ejecta masses of $\sim 10\,M_{\odot}$. Here, the observed characteristics of the absorption feature in GRB 990705 can be achieved with rather unspectacular values of $P_{\rm cl}^{\rm l.o.s.}/X_{\rm Fe} \sim 1$. The only current GRB model which could produce this combination of pre-GRB supernova ejecta and time delay, seems to be the supranova model (Vietri & Stella 1998). However, it is unclear whether the problems mentioned in Section 2 (i.e., the rather large baryon contamination and small available energy resulting from realistic simulations of such a scenario) can be overcome with strong beaming of the GRB ejecta. More detailed simulations of the supranova model are needed to clarify these issues.

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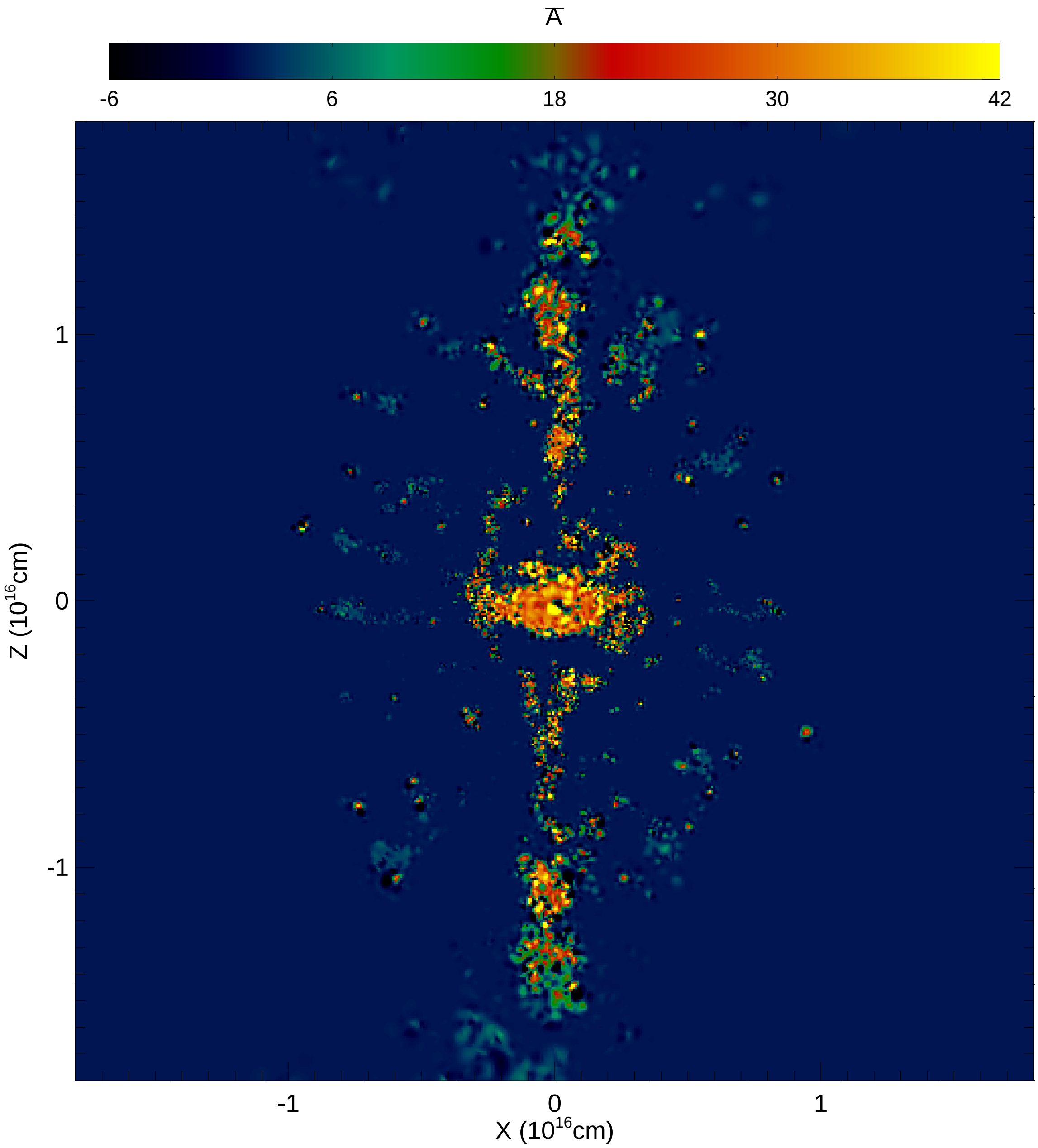

Fig. 1.— 3D simulation of a supernova explosion of a $15\,M_{\odot}$ star (for details see Fryer, Hungerford, & Warren (2001)). The figure shows the distribution of the ejecta, color-coded by the average atomic weight, 1 yr after the SN explosion.

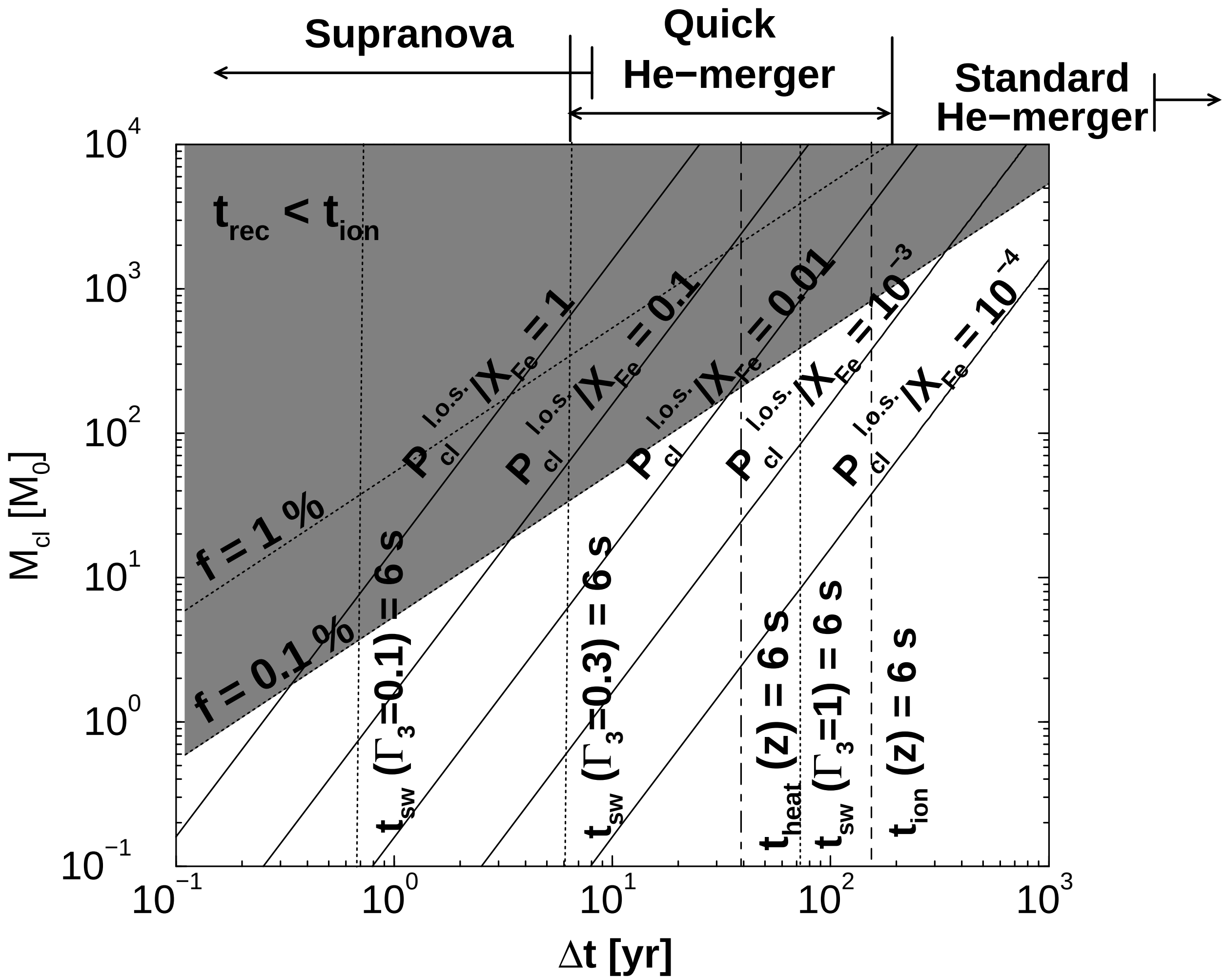

Fig. 2.— Parameter space of supernova ejecta mass $M_{\rm cl}$ concentrated in clumps, and time delay Δt between the primary's supernova explosion and the GRB. The solid lines indicate the condition that an iron Kα absorption edge of the depth observed in GRB 990705 is produced, for various values of the ratio of the probability $P_{\rm cl}^{\rm l.o.s.}$ of an absorbing cloud being located in the line of sight, to the iron enhancement $X_{\rm Fe}$ w.r.t. standard solar-system values. Constellations which would give a consistent physical scenario, must either be located close to the vertical line corresponding to $t_{\rm ion}(z) = 6$ s (if recombination is inefficient), or within the shaded regions in the upper left corner of the plot, which indicates the condition $t_{\rm rec} \leq t_{\rm ion}$ for volume filling factors of the SN ejecta of 1 % and 0.1 %, respectively, 1 year after the SN.

Table 1. Parameters of the absorber in GRB 990705, from progenitor-model independent estimates. $M_{\rm Fe}$ is the total mass of iron in the absorbing material,r_c is the radius of dense clumps containing iron-enriched material, x is their average distance from the burst source, and n_c is their average density. τ_T is the Thomson depth of the absorber, and Ω is the solid angle subtended by the absorber as seen from the burst source. The iron abundance in the clumps is parametrized as $X_{\rm Fe} = 10\, X_1^{\rm Fe}$ times the standard solar-system value, and L_{51} is the luminosity of the prompt burst radiation in units of 10^{51} ergs s^{-1}.

Quantity	$M_{\rm Fe}\,[M_\odot]$	r_c [cm]	n_c [cm^{-3}]	x [cm]
Recomb. ineff.	$44\,\Omega$	undet.	undet.	4×10^{18}
Photoel. abs. in dense cl.	$0.7\,\Omega$	$\frac{7.5\times10^{13}}{\Omega\, X_1^{\rm Fe}}$	10^{11}	2×10^{17}
Resonance scat. in dense cl.	$1.3 \times 10^{-3}\,\Omega$	$2 \times 10^{13}\,\tau_T^2\, X_1^{\rm Fe}$	$\frac{8\times10^{10}}{\tau_T\, X_1^{\rm Fe}}$	$3 \times 10^{16}\, L_{51}^{1/2}$